

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE Feb 95		3. REPORT TYPE AND DATES COVERED Final 20 May 91-31 Dec 94
4. TITLE AND SUBTITLE Quasi-Optical Millimeter Wave Power Combining			5. FUNDING NUMBERS DAAL03-91-G-0160	
6. AUTHOR(S) C.J. Summers, J.C. Wiltse, H.M. Harris, R.W. McMillan, A. Torabi				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Georgia Institute of Technology Atlanta, GA 30332			PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING / MONITORING AGENCY REPORT NUMBER ARO 28339.9-EL	
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
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14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED			18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	
19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED			20. LIMITATION OF ABSTRACT UL	

# **Quasi-Optical Millimeter Wave Power Combining**

## **FINAL REPORT**

by

**C.J. Summers, J.C. Wiltse, H.M. Harris,  
R.W. McMillan and A. Torabi**

**February, 1995**

**U.S. Army Research Office  
Contract DAAL 03-91-G-0160**

**Georgia Tech Research Institute  
Georgia Institute of Technology  
Atlanta, GA 30332**

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Georgia Tech Research Institute Georgia Institute of Technology Atlanta, GA 30332-0800			8. PERFORMING ORGANIZATION REPORT NUMBER  None	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709-2211			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
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13. ABSTRACT (Maximum 200 words) An investigation was conducted to develop power combining from planar arrays of solid-state sources at K <sub>a</sub> -band. The principal effort was concentrated on HEMT sources arranged on rectangular grids and operated at frequencies between 25 and 46 GHz. These oscillator arrays were utilized in a semi-confocal resonator, which provides feedback from one device to the others. Very narrow spectra were obtained. Grid performance was studied for arrays of 1 X 3, 3 X 1, 3 X 3, 4 X 1, 4 X 4, and 6 X 6 devices. The designs for the grids and resonators and the measured results for the arrays have been published. A problem with substrate modes was investigated and methods of improvement developed. Very significant contributions to this effort were made by Dr. Donald Griffin, who worked on the program for five months during 1993 while on leave from the University of Adelaide, Australia. Dr. Griffin was a co-author of several articles published during the project.				
14. SUBJECT TERMS K <sub>a</sub> -band arrays; Millimeter-wave power combining; Quasioptical sources; Solid-state arrays; Substrate modes			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT  UNCLASSIFIED	18. SECURITY CLASSIFICATION  UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT  UNCLASSIFIED	20. LIMITATION OF ABSTRACT  UL	

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## FORWARD

The research described in this report was based on concepts advanced earlier by Dr. James W. Mink, then of the Army Research Office. His analyses for quasi-optical power combining from solid-state source arrays have formed a strong basis for a number of investigations in this field in recent years. Previous studies dealt with microwave arrays, while the present one was the first to deal with millimeter-wave arrays of FETs and HEMTs. Dr. Mink served as the A.R.O. technical monitor for the majority of this project, and the authors would like to express appreciation for his advice and contributions.

## FINAL REPORT

### Statement of Problems Studied

An investigation was conducted to develop power combining from planar arrays of solid-state sources at  $K_a$ -band. The program was initiated by evaluating the sources that would be most appropriate at millimeter wavelengths, including IMPATT and Gunn diodes, as well as HBT, FET, and HEMT transistors. The latter two were chosen because they offer the most potential and are relatively inexpensive at  $K_a$ -band. The sources were arranged in rectangular grids which were operated at frequencies between 25 and 46 GHz. The oscillator arrays were utilized in a semi-confocal resonator, which provides feedback from one device to the others. Very narrow spectra were obtained. The nature of coupling as well as grid performance has been studied by fabricating grids with a single device,  $1 \times 3$ ,  $3 \times 1$ ,  $3 \times 3$ ,  $4 \times 1$ ,  $4 \times 4$ , and  $6 \times 6$  arrays. The grid and resonator designs and the measured results for the arrays have been reported in the literature (see the attached list of publications). A significant problem was discovered with substrate modes, which cause some power not to be collected in the resonator. This was investigated in detail and methods of improvement were developed (see items 7, 8, and 9 in the list of publications).

There is a strong need for high power, solid-state sources at millimeter-wavelengths. At lower frequencies, waveguide or cavity combiners have been successful, but at millimeter-wavelengths this approach has problems in terms of loss, power output and dimensional tolerances. In the past few years, significant efforts have been carried out at lower microwave frequencies to develop planar arrays of solid state oscillators or amplifiers in regular arrays in order to produce spatial power combining. Some of these structures have used open Fabry-Perot resonators for coupling the sources and to provide coupling between adjacent elements to provide the feedback path. Sources employed have included Gunn or IMPATT diodes, or FETs, HEMTs, or HBTs, with the three-terminal devices currently producing the best overall performance. When the current program started (1991) no millimeter-wave investigations had been reported in which transistors had been used, although millimeter-wave investigations had been described wherein Gunn oscillators or IMPATTs had been employed. The state of the art in solid-state power combining was summarized in 1992 (see item 1 in the list of publications).

The program included making tradeoffs to decide on the type of source to be utilized, analyzing and designing the grid arrays on which to mount the sources, and testing various arrays at frequencies near 35 GHz to define their characteristics in order to build optimized configurations. The investigation has centered on using a semi-confocal Fabry-Perot resonator, with the array of sources placed on the planar reflector of the resonator. The resonator consists of two surfaces that are large with respect to the wavelength. One reflector surface is flat and the other is curved and partially transparent. Power is extracted from the planar source array to the lowest order or Gaussian mode of the resonator. Useful output energy is extracted through the curved reflector with a well-defined spatial distribution. Feedback within the

resonator, and mutual coupling between the sources, causes them to be phase-locked producing single-frequency operation.

Power output measurements provide important information for interpreting the significance of the frequency measurement data in relation to the way these transistor grid oscillators function at K<sub>a</sub>-band compared with modus operandi assumed from X-band studies. For the small arrays tested it appears that the radiation pattern is broader than expected because only a small fraction of the millimeter wave output is intercepted by the front reflector of the open resonator. This was verified by placing an electromagnetic horn and power sensor over the transistor grid oscillator and adjusting operating conditions to optimize output. From these and other measurements made in the space outside the resonator, it was concluded that a significant amount of array power was being converted into substrate modes, and that this was a basic problem because of the thickness (in wavelengths) of the substrates. As a result a thorough investigation of the substrate mode problem was conducted, and the results have been reported in items 7, 8 and 9 of the list of publications.

#### Summary of Most Important Results

Numerous transistor grid oscillator arrays were built and tested at frequencies between 25 and 46 GHz. Two different semi-confocal Fabry-Perot resonators were employed. This was the first-reported investigation of FETs and HEMTs in power-combining arrays at millimeter wavelengths. The discovery of substrate modes uncovered a basic problem for oscillator arrays at millimeter wavelengths. This latter problem needs further investigation, but because of reduction of funds on the contract, this could not be carried out. The initial program amount for this contract was \$908,518, to be funded in increments. However, only \$584,743 was received, because of funding cut-backs. Nonetheless, solutions for the substrate mode problem have been developed, and these modes are not felt to be a fundamental limitation for millimeter-wave source arrays.

#### Acknowledgements

Both Dr. Donald Griffin and Mr. Stan Halpern made very important contributions to this project, and are listed as co-authors of some of the published papers. Dr. Griffin worked on the program for five months during 1993 while on leave from the University of Adelaide, Australia. Mr. Halpern was responsible for the fabrication of the transistor grid arrays.

#### List of Publications

1. J. C. Wiltse and J. W. Mink, "Quasi-Optical Power Combining of Solid-State Sources", Microwave Journal, Vol. 35, pp. 144-156, February, 1992.
2. J. C. Wiltse and J. W. Mink, "Quasi-Optical Power Combining of Millimetre Wave Sources," Proc. of the Fifth Australian Symposium on Millimetre and Submillimeter Waves, Adelaide, South Australia, pp. 22-23, August 11-13, 1992.



3. J. W. Mink and J. C. Wiltse, "Progress in Quasi-Optical Power Combining", Proc. S.P.I.E. Seventeenth International Conference on Infrared and Millimeter Waves, Pasadena, CA, pp. 68-69, December 14-17, 1992.
4. A. Torabi, H. M. Harris, R. W. McMillan, J. C. Wiltse, D. Gagnon, S. M. Halpern, and C. J. Summers, "Planar Grid Oscillator for Quasi-Optical Power Combining at 37 GHz", Proc. Fourth International Symposium on Space Terahertz Technology, Los Angeles, CA, pp. 80-93, March 30-April 1, 1993.
5. J. W. Mink and J. C. Wiltse, "Progress in Quasi-Optical Power Combining", Proc. of the Microwave and Optronics Conference (MIOP '93), Sindelfingen, Germany, pp. 340-342, May 25-27, 1993.
6. H. M. Harris, A. Torabi, R. W. McMillan, J. C. Wiltse, C. J. Summers, S. M. Halpern and D. W. Griffin, Quasi-Optical Power Combining of Solid State Sources in  $K_a$ -Band, Digest of the IEEE International Microwave Symposium, Atlanta, GA, pp. 159-162, June 15-17, 1993.
7. J. C. Wiltse, A. Torabi, H. M. Harris, R. W. McMillan, S. W. Halpern, D. W. Griffin, and C. J. Summers, "Power Combining Arrays at  $K_a$ -Band", Proc. of the Workshop on Millimeter-Wave Power Generation and Beam Control, Huntsville, AL, pp. 265-274, September 14-16, 1993.
8. H. M. Harris, A. Torabi, R. W. McMillan, D. W. Griffin, S. M. Halpern, J. C. Wiltse, and C. J. Summers, "An Antenna Array Approach to the Design of Normal Mode Transistor Grid Oscillator Power Combiners", op cit., pp. 219-227.
9. D. W. Griffin, A. Torabi, H. M. Harris, R. W. McMillan, S. M. Halpern, J. C. Wiltse, and C. J. Summers, "Millimeter Wave Substrate Mode Transistor Grid Oscillator Power Combining", op cit., pp. 219-227.
10. J. C. Wiltse, "Quasi-Optical Systems and Challenges", IEEE International Microwave Symposium, Workshop Digest WFFA, San Diego, CA, pp. B-1 to B-11, May 27, 1994.
11. R. W. McMillan, C. J. Summers, A. Torabi, H. M. Harris, J. C. Wiltse, and D. W. Griffin, "Quasi-Optical Power Combining Arrays at  $K_a$ -Band", Digest of the Third International Conference on Millimeter-Wave and Far-Infrared Science and Technology, Guangzhou, China, pp. 425-428, August 22, 26, 1994.



### List of Scientific Personnel

The co-principal investigators were Drs. Christopher J. Summers and James C. Wiltse. Other scientific personnel include Dr. Donald Griffin (on leave from the University of Adelaide, Australia), Stanton M. Halpern, H. Michael Harris, Dr. Robert W. McMillan, John Sevic, Dr. Abbas Torabi, and Dr. Brent Wagner. Of these, Mr. Sevic was a post-master's degree, Ph.D-track student. Brent Wagner received his Ph.D. after the initiation date of the contract.